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THE HELIUM CONSERVATION PROGRAM OF THE DEPARTMENT OF THE INTERIOR

By Charlotte Alber Price[*]

For almost thirty years people believed that helium existed on the sun but not on the earth. Identified by a curious yellow line in the spectrum of sunlight in 1868, helium was not found on earth until 1895. Today, helium has uses which range from the frivolous to the indispensable. The same material which makes children's balloons sail into and beyond the trees is also essential for attaining temperatures close to absolute zero. For helium is both the only inert lifting gas and the only material ever discovered which remains a liquid down to absolute zero.

Helium is a minor constituent of the air—present at a concentration of 5 ppm by volume—and is very expensive to recover. By a set of geological accidents, however, helium also turns out to lie trapped in underground gas formations in concentrations as high as 2 percent, and most of the available helium on earth is found as a minor constituent of the natural gas from the fields of a limited area of Kansas, Oklahoma, and Texas. This gas is available at about one-fiftieth of the cost of obtaining it from the air.

The helium originally got into the underground gas formations by the radioactive decay of uranium, thorium, and their decay products. (In these decays the nuclei of helium atoms are emitted.) Uranium and thorium are present in rocks like granite to the extent of a few parts per million, and the radioactive isotopes in question have half-lives of billions of years. Thus, over the entire history of the earth, helium has been collecting underground one atom at a time. Before this century ends we probably will have released most of that trapped helium into the atmosphere, except to the extent that it is recovered and stored for future use.

Until recently most of the helium in natural gas was never sep-

arated from the rest of the natural gas. Instead the helium-bearing gas was piped to consumers and burned for its energy content. In the process the helium (which is inert and therefore does not burn) was "gone with the wind."

This essay concerns an effort by the United States Government to do something about the waste of helium. Spurred on by a widespread practical concern in the scientific community, the Bureau of Mines of the Department of the Interior greatly expanded its traditional role as the manager of the nation's helium resources by developing a Helium Conservation Program, which was enacted into law in 1960. After working well for nearly a decade, the program got into financial difficulty and is now under attack from several quarters. After discussing briefly some of the uses of helium and its sources, I shall describe the manner in which the program was established and why it is in difficulty.

The Helium Conservation Program is strongly supported by the private helium industry (which may be receiving an indirect subsidy because of pricing prescribed by legislation), the scientific community (particularly those members whose work involves low temperatures only obtainable with helium), geologists who are aware of its scarcity, and the author, who is an economist, but apparently has a different preference function between the present and the future than many of her colleagues.

The Commodity and Its Sources

Helium occurs in nature in mixtures with other substances, but not in chemical combinations. Almost all of it is helium-4, the isotope whose nucleus is the famed "alpha particle" of radioactive decay.[1] Helium is the second most abundant element in the sun, after hydrogen, and the second most abundant in the whole universe, again after hydrogen. On earth, it is present in trace quantities in the atmosphere, like the other inert gases (sometimes called noble gases).[2] Because it is so light helium is continually escaping from the atmosphere into space, but the supply in the atmosphere is being replenished by alpha particles which originate from the radioactive decay of uranium and thorium in rocks near the earth's surface.

Because some rocks rich in uranium and thorium happen to have underlain airtight "domes," helium is also found in gas formations under the ground. Most of the time the gases trapped with helium are the combustible gases methane and ethane,

which are produced when organic matter is buried. This combustible "natural gas" has been greatly exploited for its energy content in the last 30 years. It is favored over coal and liquid petroleum for many purposes because it is "clean" (*i.e.*, because it burns without leaving behind ash or giving off sulfur oxides). When helium is contained in natural gas, it serves only to dilute the energy content of the gas, but since concentrations almost never exceed 2 percent by volume, this is never a nuisance, and instead the "nuisance" has always been to recover helium from the natural gas. At what concentrations it "pays" to extract helium from natural gas will depend on demand and on available technology. In 1960, Congress defined "helium-bearing natural gas" as natural gas containing at least 0.3 percent helium by volume.

Helium is also found in some noncombustible gas deposits. One deposit in Arizona has helium at a concentration of over 8 percent, associated with nitrogen. Other noncombustible deposits are in Wyoming, Utah, New Mexico, and Saskatchewan, Canada. Helium recovered from noncombustible gas is likely to be more expensive than helium recovered from combustible gases, because there is no natural gas by-product. Indeed, it is hard to see the justification, from a resource policy standpoint, of exploiting these sources of helium at all until the natural gas fields (which are being exploited anyway for their combustible product) are exhausted.

Very little attention has been paid in the United States to the elimination of wasted helium by recovery at the point of use. Practices to assure the recovery and recirculation of helium which are standard in laboratories and industrial plants in several other countries are rarely found here, or even encouraged.

Uses of Liquid and Gaseous Helium

The properties of materials at very low temperatures can, in most instances, be explored only by immersing the materials in a very low temperature liquid. Helium at atmospheric pressure is a gas down to 4.2° Kelvin (degrees Kelvin are centigrade degrees above absolute zero) and is a liquid from 4.2° Kelvin all the way down to absolute zero. Every other substance becomes a solid before absolute zero is reached. At atmospheric pressure, the coldest liquid other than helium is hydrogen, which solidifies at 14° Kelvin. Thus, to study or exploit the properties of a substance in the vicinity of absolute zero, the substance is immersed in liquid helium.

Out of studies of these low temperature properties (often called *cryogenic* properties) has come the discovery of materials which at very low temperatures have no electrical resistance (a phenomenon known as superconductivity). Superconducting helium-cooled cables may someday become an important method of transmitting electricity over long distances. Superconducting wires, carrying large currents at lower power loads than ordinary wires, have been coiled into loops to create the most powerful magnets ever known. These magnets, already useful in high energy physics and plasma physics research, are on the verge of being useful for commercial applications as well. In the long-term future, one application will almost surely be controlled nuclear fusion, which promises to permit energy to be produced with less air pollution than in fossil fuel plants and with less radioactive wastes than in fission reactors.

Although commercial uses of liquid helium are growing rapidly, and the volume consumed grew tenfold between 1962 and 1967, it is still true today that most helium use is a consequence of its desirable (and often unique) properties as a gas. Until World War II, helium demand was tied to the fortunes of lighter-than-air ships and thus to congressional appropriations for dirigibles and blimps.[3] Helium, because of this application, is classed as a "munition," and a special license is required to export it.

The use of helium has grown dramatically in the last 20 years. The ability of helium to diffuse rapidly through microscopic openings, its inertness, and its easy distinguishability make it ideally suited for use in leak detection. Helium-oxygen mixtures are often prescribed for asthma patients, because the helium carries the oxygen deeper into lung passages, as a result of its rapid diffusion. Helium gas is also used in a mixture with oxygen as a substitute for ordinary air in the breathing mixtures used by deep-sea divers—nitrogen at high pressures is a deadly intoxicant.

One of the most remarkable of the new uses of helium is in the space program. As a result of its inertness, helium, as a gas under pressure, has turned out to be invaluable for moving two highly reactive gases from separate chambers to a central reaction region without interacting with either of them. Thus on board the Apollo flights liquid oxygen, liquid hydrogen, and liquid helium are found. Oxygen and hydrogen combine (to make water) in the rocket engine, and helium is the agent that brings them together

TABLE 1

USES OF HELIUM, 1967

Application	Volume (million cubic feet)	Percent of Total
Pressurizing and purging	370	40.8
Controlled atmospheres	105	11.6
Research	101	11.1
Welding	97	10.7
Lifting gas	69	7.6
Leak detection	64	7.1
Cryogenics	51	5.6
Chromatography	22	2.4
Heat transfer	14	1.5
Other	14	1.6
Total	907	100.0

SOURCE: U. S. Bureau of Mines, Helium Activity.

in a controlled fashion. Helium is preferred over any of the other inert gases because of its light weight.

Of the numerous other uses of helium, we shall mention just one more—welding. (A breakdown of helium use by application is seen in Table 1.) Because helium does not combine with other substances, even at high temperatures, it is desirable to bathe a welding site with helium during the welding process, to prevent corrosion of the surfaces as they are being joined. For this purpose, lightness is not always a particular virtue, and argon is sometimes substituted for helium in welding applications.

THE DEVELOPMENT OF A CONSERVATION PROGRAM

From 1937 to 1961, helium production was a government monopoly. The Bureau of Mines built and operated "helium activity" plants, extracting helium from both combustible and noncombustible sources. Helium conservation had taken the form of storing excess production from plants recovering helium from pipeline gas, but recovery and storage were on a small scale.

In the late 1950's the critical shortage of helium—before the newest of the Bureau of Mines plants (at Keyes, Oklahoma) was opened—apparently led the government to undertake a study of potential helium sources. The new plant at Keyes was to recover helium from a hydrocarbon gas field found in 1943, and it was

sobering that every gas field discovered in the interim 15-year period had contained much less helium. During those same 15 years, a great deal of natural gas exploration and discovery had taken place and the Bureau of Mines had regularly tested samples from new wells for helium content.

The study was also stimulated by projections of large increases in demand for helium over the three or four decades ahead. The projections in part reflected the surge in demand at that time, but were also reinforced by laboratory developments during the 1950's. It was assumed by scientists working with helium that some of the phenomena being studied then would result in engineering "payoffs" some time in the distant, although foreseeable, future. These scientists foresaw new processes and products which would require very low temperatures, temperatures only available with the use of liquid helium.

Most of the known extensive sources of helium in the United States were (and are) in hydrocarbon natural gas that was already committed to distribution and use. Hence, unless the helium was extracted and stored before distribution, it would not be available later. Yearly demand at that time was almost 500 million cubic feet,[4] while more than 5 billion cubic feet were being released into the air annually with the marketed helium-bearing natural gas.

Two alternatives to recovery and storage (considered, but rejected in the 1950's) were (1) to let a conservation program take over the fields containing helium and operate them only when the helium was required or (2) to require the natural gas producers to recover and store or sell helium before they could market the hydrocarbon gas in interstate commerce. Both notions were rejected because they were considered politically infeasible as well as unjustifiably expensive. It was believed that Congress, the Federal Power Commission, and both producers and consumers of natural gas would oppose the restraints on gas supplies dictated by the alternatives.

The program that was proposed in 1960 and subsequently adopted had the following characteristics. (1) Under long-term contracts, the natural gas distributors whose source gas came from the extensive Hugoton and Panhandle fields in Kansas, Oklahoma, and Texas—discovered prior to World War II—were to build plants to recover the helium from the natural gas before it was distributed and to sell the helium to the federal government. (2) The government was to build a pipeline to transport the re-

covered helium from the recovery plants to a partially exhausted gas field (the Cliffside structure, near Amarillo, Texas) which it controlled since the 1920s. (This structure had been used to store excess helium during the late 1940s; then, when demand increased very rapidly in the mid-1950s, 85 million cubic feet of helium was retrieved from storage.) (3) Finally, a pricing policy for the *sale* of helium was designed with the intention of recovering, over a period of 24 to 35 years, all of the costs of the conservation program.

The government's selling price of helium, which at the time was $15.50 per thousand cubic feet for government agencies and $19 per thousand cubic feet for everyone else, was to be raised to $35 per thousand cubic feet for everybody, and the increased receipts from sales were to be allocated to pay the costs incurred in the purchasing of helium for conservation.[5] Although initially, the costs of purchases for conservation were expected to exceed revenues from sales, and the difference was to be made up by borrowing from the United States Treasury, later (the crossover date was estimated to be around 1970) revenues from sales were expected to exceed costs, including interest on the borrowed funds. The entire program was to be administered by the Bureau of Mines, the agency (now within the Department of the Interior) which had been responsible for helium production since 1925.

When helium conservation legislation was before Congress, numerous amendments were added. The thrust of the amendments was to encourage the entry of private industry into the helium market. Yet the original concept of financing the program out of government sales of helium was retained. The amended legislation, with general bipartisan support, was passed in September 1960, and in August 1961 the program was authorized to spend $47.5 million per year for a 22 year period.

By November 1961 contracts for the purchase of helium from five helium-extraction plants (which were to be constructed) were negotiated with four private firms. Under these contracts the government expected to purchase up to 3.5 billion cubic feet of helium a year for 20 years. (This represents about four times the rate at which helium has been used in the last few years and 60 percent of the helium that was then being wasted by not being extracted from marketed natural gas.) The contracts set an initial purchase price between $10 and $12 per thousand cubic feet and provided annual dollar ceilings on how much the government

agreed to purchase from each supplier. In letting out these contracts all of the authorized funds were committed. The Bureau of Mines has since asked for authorization to spend up to $65 million per year in order to increase the amount of helium it could buy for storage, but more funding has not been granted.

In 1960 the total known reserves of helium in helium-bearing natural gas amounted to 154 billion cubic feet. The amount of helium predicted to be available after 1985 with and without the program was 87 billion versus 35 billion cubic feet. The difference, 52 billion cubic feet, would go into the air in marketed natural gas without the program.

Initially the program worked as planned. By mid-1969, 22 billion cubic feet of helium had been stored in the Cliffside field, and the demand for helium was rising according to expectations through 1967. Problems then arose in the financing of the program. These problems were rooted in inconsistencies which had been built into the original legislation. These problems were exacerbated by the high interest rates for Treasury borrowing of the late 1960s.

Setting the price of government-sold helium artifically high was a successful way for the government to earn revenues only so long as the government held a monopoly on helium sales. However, because the enabling legislation had sought to encourage the entry of private industry into the helium market, and all of the planned helium conservation plants had not been built (leaving desirable helium-bearing natural gas still going to market), the government's monopoly was undermined. It was inevitable that the high government selling price would encourage the development of competition from private industry. By 1966, three private plants were in operation, and these new plants were underselling the government.

By 1970 private industry accounted for nearly half of the helium sales. Some of the sales came from the same plants which were supplying the helium to the conservation program, because they were producing helium at a rate faster than the government was permitted to buy it. The reason that the Bureau of Mines was able to sell any helium was that federal agencies were required by law to make all major purchases from the government. The courts had decided that private contractors working for the federal government were not bound by the same restrictions on government purchasing as the government agencies themselves, although the

Bureau of Mines had attempted to get the opposite ruling. And on top of all of this, total helium consumption, which had reached a peak of 948 million cubic feet in 1966, dropped to 760 million cubic feet in 1969, primarily as a result of cutbacks in the space program. In brief, the government was not securing the revenues from sales which the enabling legislation had required, precipitating a budgetary crisis, which, at the time of this writing, has not been resolved.

Prospects

It is clear that a program designed to conserve helium for use many decades into the future would not be a wise investment of government funds if there were a reasonable prospect of obtaining adequate quantities of helium in the future at the same or a lower cost from some other source. To make a quantitative comparison, one must find a way of computing the cost in the future of storing helium now. That cost, called the *implicit cost*, is the sum of the initial cost (about $12 per thousand cubic feet) and the interest on that cost, compounded over the period the unit of helium is in storage. Choosing the appropriate interest rate is a critical and controversial matter. Over a few decades of accumulation, even one percentage point increase in this rate may spell the difference between a program that can or cannot be justified before Congress.[6]

One must also estimate the costs associated with the sources of helium that will be available. The three likely sources are the air, possible power plants using nuclear fusion, and remaining deposits of natural gas.

1. *Helium from Air.* Helium and neon could be available as by-products of the liquefaction and separation of air, which is today a large-scale industrial process primarily designed to recover oxygen. Practical considerations indicate, however, that this source is inherently a minor one. At present levels of oxygen recovery in the United States, the helium *potentially* available (it is not now collected) is about 10 million cubic feet per year. There is no reason to believe oxygen demand will grow at many times the rate of growth of helium demand. Yet unless such a relative growth rate occurs, by-product helium could not be produced in quantities sufficient to supply even nonsubstitutable uses, say, 50 years from now.

In the process of recovering helium from air, three and one half

times as much neon becomes available at the same time, since neon is present in a concentration of 18 ppm versus 5 ppm for helium. Neon, the second lightest of the noble gases, presumably would be cheaper than helium, and might be used as a substitute for helium in some functions. If helium alone were to be obtained from air at present technology, it would cost $10,000 per thousand cubic feet; by-product helium is likely to cost $600 to $800 per thousand cubic feet.

2. *Fusion Power.*[7] Energy may ultimately be generated by nuclear fusion. If it is, helium will be a by-product, because the basic process involves the fusion of two hydrogen nuclei to make a helium nucleus. Any fusion process, however, is likely to require large magnetic forces; the source of the latter is very likely to be superconducting magnets at liquid helium temperatures. Engineering calculations seem not to have been made on whether a fusion power plant will be a net user of helium or a net supplier. The critical question seems to be the extent of helium losses within the system. It is unlikely, however, that fusion reactions will ever be a significant source of helium. Even if a fusion process is developed which does not require superconducting magnets, and even if all of the helium is recovered and available for other uses, the total helium production is small. Only 10 million cubic feet per year would be produced if an amount of electricity equal to the total current U.S. production of electricity were generated by the fusion process in plants converting nuclear energy to electrical energy at 20 percent efficiency. Less helium would be available if the plants were more efficient.

3. *"Leaner" Deposits of Natural Gas.* These deposits will probably be the cheapest alternative source of helium. It is likely that improvements in technology will reduce the costs of extracting helium present in very low concentrations in natural gas. A crucial question, however, is whether substantial quantities of natural gas will still be recovered 40 years or more hence. A recent National Academy of Sciences study predicted that natural gas sources in the United States, and perhaps the rest of the world, will be nearing exhaustion during the first decade or so of the twenty-first century.[8] If that estimate is in fact, accurate, comparing the cost of extraction from "leaner deposits" with the implicit cost of stored helium 40 to 50 years from now becomes an academic exercise.

Any detailed comparison of the implicit cost of stored helium

at some date in the future with the alternative cost of producing helium at same date directly (by any process) obviously involves one in guesswork. One must make assumptions about both future production and future consumption. One must choose an interest rate to calculate implicit cost, and one must estimate future production costs for alternative processes. The author did nearly a score of estimates, using various assumptions about future demand and production, all of which indicated that the implicit cost of helium stored by the conservation program would be significantly less than the cost of by-product recovery from air, during the entire period that the stored helium would last.[9]

However, another economist, Professor Lee Preston, of the State University of New York at Buffalo, has testified before Congress that the helium conservation program cannot be justified on economic grounds. His conclusions are very different from mine primarily because he is willing to be much more optimistic than I am concerning the future discovery of yet unknown natural gas fields. He is also counting more than I on new technology which will be able to lower the cost of extraction of helium from deposits substantially leaner than those with 0.3 percent concentration. Finally, he is not expecting demand for helium to rise significantly from current levels. Professor Preston's conclusions are being used by some members of Congress and of the Bureau of the Budget to support a proposal to the effect that the Bureau of Mines should immediately abandon the acquisition of helium for conservation.

The author does not believe that the underlying premises of the conservation program have been invalidated by the developments of a financial nature of the last two years. The way to solve a financial problem is with alterations in the structure of the financing. One way to continue the helium conservation program under redesigned financing would be to tax all sales of helium a fixed amount (say $10 per thousand cubic feet), using the revenue to pay for the conservation program. Another way would be to postpone the time at which the program is required to repay its loans from the United States Treasury until such time as the helium in storage is sold.

If the conservation program is allowed to function as was originally proposed, with some new financing provision, then by 1983, when the program ends, approximately 62 billion cubic feet of helium will have been recovered instead of wasted. How much of

this would then be in storage would depend on whether demand had required using some of what would otherwise have been stored. There would seem to be every reason to extend the program beyond 1983 and to continue to attempt to conserve as much as possible of the helium still in the ground at that time.

It was 41 years ago (May 1930) that a congressional committee held special hearings on the new government-owned Amarillo Helium Plant and its complementary helium-bearing Cliffside gas field. During the course of testimony it was explained that the gas field had enough helium to last for 200 to 300 years. At the consumption rate of that period, 8 million cubic feet per year, that was a proper estimate. In recent years, consumption of helium has been about 100 times that of four decades ago, but now the conservation program is being attacked on the grounds that current known resources plus helium already in the Cliffside structure (by virtue of the helium conservation program) are more than adequate for the next 40 years. This is the kind of prediction which, if wrong and followed, represents an irreversible decision. Forty years from now, if the forecast proves to be wrong, recovering the wasted helium from the air will be prohibitively costly. It would seem prudent to base natural resource policy on an approach that, if it errs at all, errs on the side of overconservation.

Postscript: Helium Waste and Entropy

By John Harte and Robert H. Socolow

Helium waste appears to be one of the more esoteric examples of the loss of a valuable resource. The possible scarcity of other more basic resources such as oil, wood, oxygen, water or rich soil are, deservedly, more in the spotlight today. Yet the helium story needs to be understood, for it illustrates in an extremely simple and clear cut manner the principle underlying the *irreversible* nature of the loss of a nonrenewable resource.

When a pocket of helium is wasted, *i.e.*, dissipated into the atmosphere, it undergoes a transition from a relatively concentrated and accessible state to a diffuse state, where it is far harder to retrieve. It is in this sense that the loss is irreversible.

The phenomenon of the irreversible loss of helium illustrates a fundamental law of nature—the second law of thermodynamics.

Let us look first at a different example which illustrates this oft-quoted law and then attempt to state the law more generally and explore its implications.

Suppose you are given a metal rod at some moment in time and it happens that the temperature of the metal at one end is greater than at the other. In other words, the molecules of metal at that time are, on the average, moving faster at one end than at the other. Suppose the rod is isolated from all external influences so that, for example, it cannot exchange heat with its surroundings. What do you expect to find if you measure the temperature at each end of the rod at some subsequent time? The end which was hotter may be even more hot, it may remain at the same temperature, or it may cool. Conservation of energy (the first law of thermodynamics) simply tells us that if the hotter end cools, the cooler end will heat, and vice versa, for the total quantity of heat in the isolated rod is constant. The second law provides more information, for it assures us that the two ends of the rod will *almost invariably* approach each other in temperature; heat will flow from the hot end to the cool end.

The basis of this law is statistical and that is why we say *almost* invariably. The odds are much much greater that the hot end will cool rather than heat up. This can be understood by considering matter at the molecular level. To any given macroscopic state of the rod, characterized by a temperature distribution along the length of the rod, there exist many microscopic states characterized by the positions and velocities of each of the molecules comprising the rod. (You might think, by way of analogy, of a party of people in a closed room. If you "measure" the macroscopic state of the party by a device that detects the total noise level, then many different combinations of the individual voices will correspond to the macroscopic state.) If you consider two *different* macroscopic states of the rod, in general, more microscopic states will correspond to one macroscopic state than to the other. (A silent room full of people can only occur if all voices are silent so that there is only *one* microscopic state corresponding to the silent state, whereas a macroscopic state with a nonzero noise level can arise from many different combinations of voices.)

In order to relate these concepts to the second law, we have to make a fundamental assumption: *all microscopic states are equally probable.* Granting this assumption, it follows that a sys-

tem is most likely to be found with a macroscopic state to which the largest number of microscopic states correspond. Hence, if the system happens to be found in a macroscopic state A to which few microscopic states correspond, and if the system could exist in a macroscopic state B with which a greater number of microscopic states are associated, then it is likely that the system will evolve from A to B.

It is possible to show, using the same kind of mathematical thinking which leads to the conclusion that of all the two-child families twice as many have one boy and one girl as have two girls, that an overwhelmingly greater number of molecular states are available for a uniformly heated rod than for a rod in which one end is hotter than the other. Thus the probability is overwhelmingly great that the nonuniformly heated isolated rod will evolve in time into a uniformly heated rod.

There is a high degree of *order* or *variety* in a rod in which the molecules are moving faster at one end than at the other. If the molecular velocities are random or unordered throughout the rod, then its temperature will be uniform. According to the second law, our original rod will evolve in time toward the state of least order, or greatest randomness.

Physicists introduce the term *entropy* to define the disorder of a system. Our original rod was in a state of low entropy (high order) and it will progress, with overwhelming odds, to a state with higher entropy. The second law of thermodynamics states that the entropy of an isolated macroscopic system will, with overwhelming probability, either increase or stay the same.[10]

Although we have used a specific example of a metal bar to introduce the basic ideas, the second law of thermodynamics is a completely general result. With the single statement that the entropy of an isolated system will almost invariably increase or stay the same the second law of thermodynamics describes how *every* isolated system will evolve.

We can now understand why certain changes are irreversible. If an isolated system increases its entropy, it is virtually impossible for it to return to its orginal state, for its entropy would have to decrease to do so, and that is what the second law forbids. On the other hand, changes in a system which keep the entropy constant (like rotating a metal rod which is at a uniform temperature) are reversible.

If the system is not isolated, then its entropy *can* decrease. To go back to our example, we can heat one end of a rod at uniform

temperature, and the entropy of the rod will decrease. But the entropy of the *larger* system, consisting of the rod plus the heat source will, if *it* is isolated, either increase or remain constant.

Returning now to helium, the underground reserves are in a state of relatively low entropy compared to the disordered state in which they are diffused into the atmosphere. Having helium molecules concentrated somewhere, rather than spread throughout the atmosphere is analogous to having the first-moving molecules in the metal bar concentrated at one end. If helium is allowed to dissipate into the atmosphere, the loss is thus practically irreversible. Only considerable external energy could retrieve the initial situation.

There are examples of the use of energy to retrieve a resource which has evolved, as a consequence of the second law of thermodynamics, into a high entropy state. If we pour salt into fresh water, we have mixed, or disordered, the two ingredients. To retrieve fresh water, we must expend energy. For example, we can boil the salt water and obtain fresh water and salt in a state of lower entropy than that of the seawater.

Another low-entropy state derived from seawater is a fish. The source of energy which allowed the slow transition from seawater to fish is the sun.

There appears to be inherent value in variety or low entropy. A low entropy ecosystem is more resilient to stress and more productive than a uniform ecosystem without variety. Similarly, a uniform mixture of paint affords no aesthetic pleasure, but a low entropy pattern of paints may be a masterpiece.

The degree of order of a system can be thought of as a nonrenewable resource; when it is wasted, the second law of thermodynamics tells us it will inevitably cost energy to bring the system back to what it was. Man is already producing energy on a scale that is causing reverberations throughout his environment. Actions of society which needlessly increase the present or future requirements for energy must be avoided; the second law of thermodynamics helps us to spotlight some of these actions.

FOOTNOTES

❖ Mrs. Price is a monetary economist. She has served on the faculties of Columbia University, Barnard College, and Vassar College.

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John Harte and Robert H. Socolow, both Assistant Professors of Physics at Yale University. *Environmental Affairs* presents this selection with the special permission of Holt, Rinehart and Winston, Inc., which publishes the book (544 pages, $4.50 paperbound) this month.

[1] A second naturally occurring isotope, helium-3, exists, although it is one million times more rare on earth. It is a remarkable substance in its own right. In liquefies at an even lower temperature than helium-4 (3.2° versus 4.2° above absolute zero on the absolute temperature scale at atmospheric pressure). [Editor's note]

[2] The proportion of the inert gases in air at about sea level is generally given as argon 0.8–1.0%, neon 18 ppm (parts per million by volume); helium 5 ppm; krypton 1.1 ppm; xenon 0.09 ppm. The amount of helium in the atmosphere is far greater than in the underground formations.

[3] Neon, the next lightest inert gas, is also lighter than air, but neon is two-thirds as dense as air, while helium is one-seventh as dense as air, when these gases are compared at the same temperatures and pressures. Since it is the difference between the weight of the gas and the weight of the air which represents the lifting capacity, neon is not useful for lifting blimps or weather balloons.

[4] When helium volumes are cited in cubic feet, this always refers to the volume at standard temperature (70°F) and pressure (760 mm of mercury).

[5] At the time, the cost of production at Keyes was about $8.00 per thousand cubic feet, and the cost was higher elsewhere.

[6] At four percent interest, a $12 expenditure becomes a $39 implicit cost in 30 years; at 10 percent interest it becomes a $209 implicit cost.

[7] Controlled nuclear fusion may become the most important source of energy for man. We are interested here in verifying that nonetheless it will not be an important source of helium.

In a fusion reaction, two nuclei combine to make either one or two different nuclei, in such a way that the total mass of the final nuclei is less than the total mass of the original nuclei. The "lost" mass reappears as the energy released in the reaction.

Numerous nuclear reactions are candidates for "the" fusion reaction. We will take for definiteness the reaction

$$D + T \rightarrow {}^4He + n + 18\ MeV \qquad (1)$$

in which a deuterium nucleus (D) and a tritium nucleus (T) collide and a helium-4 necleus, a neutron, and 18 MeV (million electron volts) of energy are produced. (Deuterium and tritium are isotopes of hydrogen). The helium-4 nucleus immediately picks up electrons to become a helium atom. If power plants use this process to create electrical energy at 20 percent efficiency, then one helium atom will be made with every 3.6 MeV of electrical energy.

The problem at hand is to calculate the amount of helium which would be produced each year if this were the process by which all of the United States electricity were produced. Using the 1969 figure that electricity was consumed at 0.75 kilowatts per person, we get an electrical energy consumption in the country in a year (200 million people, 3×10^7 seconds in a year) of 4.5×10^{18} joules, or 3×10^{37} electron-volts (eV). Since 1 MeV $=10^6$ eV, we find that 8×10^{30} helium atoms would be produced. Now, 6×10^{23} atoms (Avogadro's number of atoms) of a gas at standard temperature and pressure occupy 22.4 liters (or 22.4/28.32 = 0.79 cubic feet), so 8×10^{30} atoms will occupy 1.0×10^7 cubic feet, that is, 10 million cubic feet. This number agrees with the number in the text. One could have obtained answers differing by a factor of 2 or so by choosing a nuclear reaction other than (1).) Thus the amount of helium currently used in the United States in about four days would be produced in a year.

[8] M. King Hubbert, "Energy Resources," in *Resources and Man*, published by Freeman and Company for the National Academy of Sciences, 1969 (p. 187 ff).

[9] Charlotte Alber Price "The Helium Industry: A Study of a Federal Government Monopoly." Ph.D. dissertation, Columbia University, New York, 1967.

[10] Our example of the bar illustrates why we have to allow the possibility that the entropy remain constant. Once the temperature is uniform, no macroscopic state is available which is more disordered and the entropy will thence forth remain constant.